Ripple Dynamics and Benthic Transformations Under Variable Wave Forcing

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LONG-TERM GOALS

Previous work has shown that sound penetration into sandy sediments at low grazing angles is enhanced when ripples are present on the seafloor. In addition, ripples may change effective seafloor roughness and cause strong wave/current attenuation. The long-term goal of our research program is to create broad scientific knowledge that underpins the development of predictive tools for ripple dynamics and benthic transformations under variable wave forcing. The main purpose is to better understand the genesis, temporal and spatial evolution and decay of small-scale ripple morphology on sandy seafloors in shallow waters for homogeneous as well as heterogeneous sediments. The principal approach is to identify, investigate and parameterize critical hydrodynamic processes and parameters that affect ripple dynamics and transformations using laboratory experiments, theoretical analyses and numerical simulations.

OBJECTIVES

The near-term objectives of our research are to: (i) study the dynamics and morphology of symmetric/asymmetric ripples generated under variable waves forcing; (ii) investigate the genesis, evolution, dislocations and decay of ripples under weak oscillatory-flow and turbulence conditions; (iii) study segregation processes that are frequently observed in field situations but practically ignored in laboratory/theoretical studies; (iv) develop models and parameterizations for ripple formation, growth, transformation and decay under variable forcing; and (v) verify the models developed using laboratory data and available field observations.

APPROACH

A comprehensive laboratory experimental and theoretical research program was conducted to investigate the dynamics of sand ripples under conditions that are close to natural environments. The main components of the program were to: (i) measure, using small-scale followed by larger-scale experiments, the spatial variability of ripple morphology under oscillatory flow and shoaling waves that are typical of coastal waters; (ii) develop models/parameterizations for ripple morphology including sediment sorting in sand mixtures; and (iii) extrapolate laboratory findings, using appropriate non-dimensional parameters, to oceanic conditions with the aim of providing guidance for the

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interpretation of field data. The emphasis was on improving physical understanding and quantitative predictive skills of flow around ripples, ripple morphology and sand sorting.

WORK COMPLETED

Significant progress has been made during the course of our research program, which includes the development of a hierarchy of ripple dynamics and scour/burial models based on laboratory, theoretical and numerical work [1-9]. In FY 07, our research focused mostly on: (i) geometry of ripples under asymmetric shoaling waves, (ii) sediment segregation in bimodal sand mixtures, (iii) ripple dynamics and bed transformations under variable wave forcing in bimodal sediments, (iv) decay of ripples under weak forcing or/background turbulence in homogeneous sediment environments. A large wave tank with shoaling waves along a sandy slope **(**see, e.g., [2,3]) and a smaller tank with an oscillatory sand rig (see [10,11]) were used in experiments. Quantitative data were obtained using three-component acoustic Doppler Velocimetry (ADV), a high-precision Laser Displacement Sensor (LDS) and a high-speed (500 f/s) video camera connected to Particle Image Velocimetry (PIV). To reduce the effect of sediment particles on PIV measurements, small nylon micro spheres illuminated by an IR laser were used (see examples in Figs. 1 and 2).

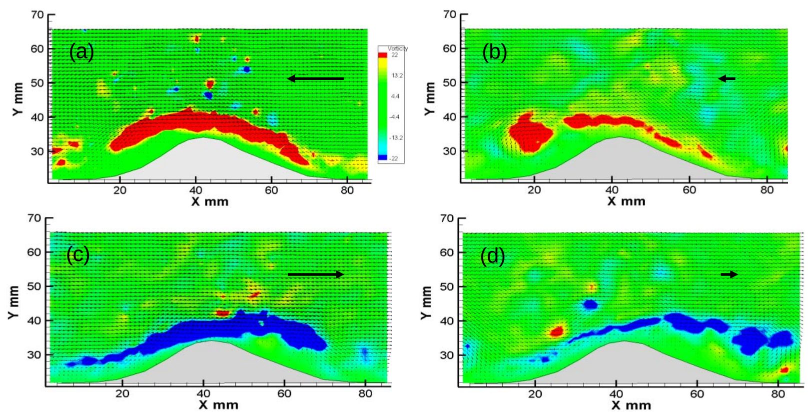

Fig. 1. Typical PIV images (a-d) of the vorticity field (different colors) in a weak oscillatory flow aloft decaying ripples at different flow phases. Large black arrows show the background flow magnitude and direction. Vorticity scale is $\pm 22\ s^{-1}$. Flow dynamics here closely resemble oscillatory flow around bottom cylinder [12,13].

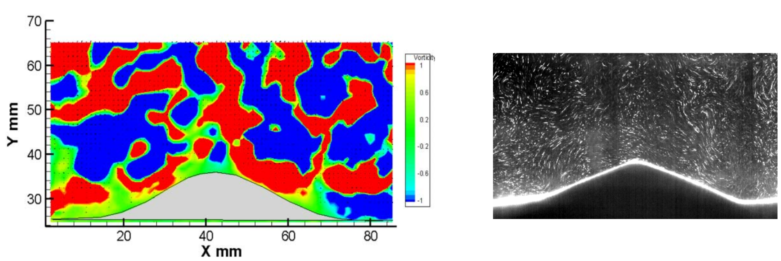

Fig. 2. Typical vorticity/velocity fields (left) and a streak photograph (right) in a turbulent flow induced above the ripples. Vorticity scale $\pm 1\ s^{-1}$. Note that the vorticity scale here is enlarged 22 times from that of Fig. 1.

The results obtained are described in [5,10-12], and the main FY 07 findings are summarized below.

RESULTS

(i) Under linear symmetric forcing, the sand ripples are symmetric, but under nonlinear shoaling waves the forcing is asymmetric, as are the ripples. Asymmetric ripples demonstrate similarity behavior, irrespective of the values of parameters used in the experiments. A model was developed to explain this behavior. A "universal" ripple profile was proposed and heuristically explained [5].

(ii) Characteristic segregation patterns in bimodally distributed sediments (Fig. 3) were identified and explained [10-12]. Although initial segregation of the fine sediment fraction mostly occurs in ripple troughs, segregation on ripple crests could be seen over time (Fig. 3a).

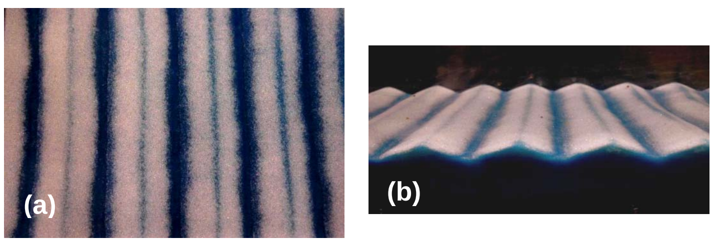

Fig. 3. Top view (a) and oblique view (b) photographs showing typical sediment segregation patterns in a bimodal mixture (blue – fine, brown - course sediment).

(iii) A general analysis shows that for a bimodal sand mixture the most important parameter is the effective grain size, d*, which is a suitably defined *rms* value of grain diameters in the mixture that takes into account the number of particles of different sizes in a unit mass of mixture [11]. Using this parameter, our previous models for ripple evolution under variable forcing in homogeneous sediments [13] were modified and tested in experiments with bimodal sediment (see, for example, Fig. 4).

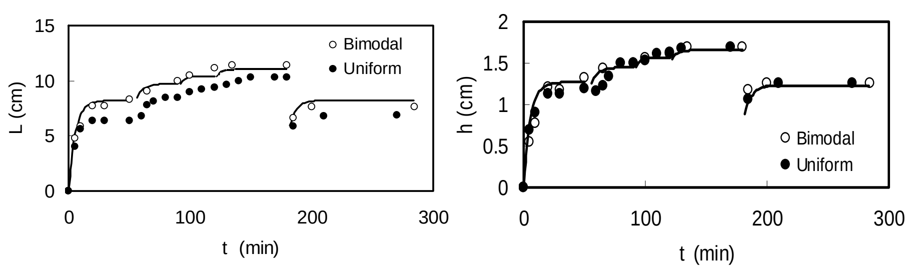

Fig. 4. Evolution of ripples of length L and height h in homogeneous and bimodal sediments under variable flow forcing. Symbols - measurements, solid lines – modified model estimates for <u>bimodal</u> mixture

(iv) The two main mechanisms responsible for ripple degradation are (i) weak forcing, below a threshold of which ripples may decay [14], and (ii) background turbulence and disturbances, for example, bioturbation [15,16]. Both of these mechanisms were studied.

Results show (see example in Fig. 5) that under weak forcing, the ripple height, h, decays with time t in accordance with a diffusion model with constant (with time) effective sediment diffusivity, i.e. $K_0(t)$=constant, viz.

$$h(x,t)/h(x,0) = \exp(-K_0 k^2 t), \quad K_0 = \begin{cases} C_0 2\pi\varepsilon\omega h_0 \left[\Psi_{cr}/\Psi - 1\right]^m, & \Psi < \Psi_{cr} \\ 0, & \Psi > \Psi_{cr} \end{cases} \quad (1)$$

($h(x,0) = h_0 \sin kx$, k=2π/L and C_0=5x10^{-7}, m=-0.5, Ψ_{cr}=5.4 are empirical constants). Note that when the mobility parameter $\Psi > \Psi_{cr}$, the ripple dynamics change and, as explained in [13], new ripples start to form by splitting or merging processes depending on flow conditions.

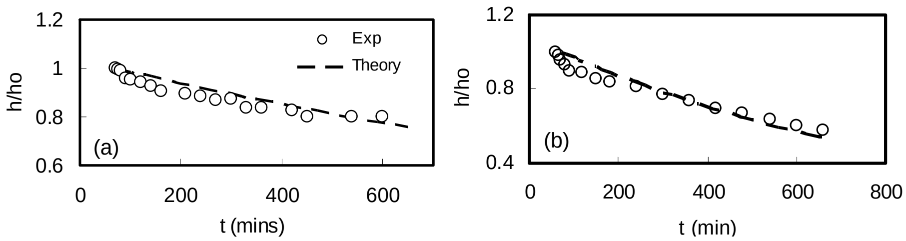

Fig. 5. The time decay of the dimensionless ripple height h/h_0 under weak oscillatory flow for two experiments (a, b) with different forcing (specified by frequency ω and amplitude ε of oscillations). Symbols – measurements, dashed lines - predictions (1). The flow was applied on established ripples when h/h_0=1.

(v) Turbulence induced by an oscillating grid or a perforated plate was used as a source of controlled external turbulence on ripples. Kindred turbulence has been studied previously [17] and thus only a selected number of experiments (for example, see Fig. 2) was needed to confirm established parameterizations for turbulence quantities. In experiments with turbulence, results qualitatively similar to those obtained for weak oscillatory flows were documented (see Fig. 6). In the former, however, the initial decay of ripples was much faster than that at later times (Fig. 6), thus defying the above model based on a constant effective sediment diffusivity.

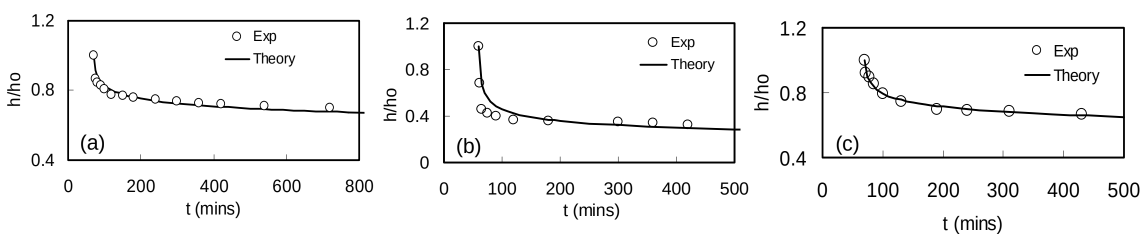

Fig. 6. Ripples decay under oscillating grid (a, b) and perforated plate (c) turbulence. Turbulence (rms) velocity u near the ripple crests - 1.1 (a, c) and 2.2 cm/s (b). Symbols – measurements, solid line – model predictions (2). The turbulence was applied on established ripples when h/h_0=1.

To explain the observed behavior, therefore, a model with variable diffusivity was advanced. In this model, as a first step, the evolution (decrease) of ripple steepness, h/k, with time was considered using a parameterization of the form $K = K_0 (kh)^n$ (K_0-initial diffusivity, n>0-empirical coefficient). This model gives an exact solution of the form,

$$h(x,t)/h(x,0) = 1\Big/\sqrt[n]{1 + (nK_0 k^{2+n} t\, h_0{}^n)}\,. \quad (2a)$$

To parameterize K_0 and n, we used following semi-empirical dependences:

$$K_0 = \begin{cases} C_1 u h_0 \left[u / u_{cr} - 1 \right], & u \geq u_{cr} \\ 0 \qquad , & u < u_{cr} \end{cases}, \; n = C_2 (u/u_{cr} - 1) \qquad (2b)$$

(u_{cr} =0.5 cm/s, $C_1=10^{-3}$, $C_2=4.2$) and solid lines in Fig. 4 are plotted based on (2). The agreement is highly satisfactory, lending support for the parameterizations employed for effective diffusivity.

The validity of (2) was also verified in experiments conducted by applying both weak oscillatory flow and turbulence on established ripples. Comparisons of model estimates with ripples decay measurements show a satisfactory agreement, and in particular it was found that in the parameter range studied both effects should be taken into account at large times. Note that field observations from SAX '04 experiments give the estimate [15,16] $K_0=(1\text{-}20)\text{x}10^{-5}$ cm^2s^{-1}, which is in agreement with predictions based on laboratory work for weak oscillatory flow, $K_0=(1\text{-}2)\text{x}10^{-5}$ cm^2s^{-1}. Our predictions based on experiments with background turbulence also yield initial values of K_0 [=(4-8)x10^{-4} cm^2s^{-1}].

IMPACT/APPLICATIONS

Ripple dynamics and sand segregation under variable forcing typical of the oceanic coastal zone are not well understood from a fundamental point of view nor have they been modeled based on phenomenological and dynamical arguments. Our work has made significant advances in this regard by utilizing integrated laboratory and theoretical/numerical approaches.

TRANSITIONS

We interacted with the field experimental groups of the University of South Florida and Woods Hole Oceanographic Institution in comparing their field results with predictions based on laboratory results. In closing out our mine burial research conducted under the previous grant, in FY07 we have compared laboratory results of scour rate, object burial and flow regimes with operational mine burial models: WISSP, NBURY and DRAMBUIE. The mine burial regime diagrams and associated formulations have been transitioned to the Mine Burial Expert System development group at JHU/APL. Experimental data, models and parameterizations developed under this project are being well used by the research community (more than 60 journal citations).

RELATED PROJECTS

The PIs are unaware of laboratory projects conducted elsewhere on the decay of ripples. Studies on sediment segregation on ripples are also sparse, and the PIs are aware of only three papers on this topic (Foti E. and Blondeaux P., Coastal Eng., 25, 237, 1995; Caps H. & Vandewalle N., Physica A, 313, 357, 2002; Rousseaux G., Caps H. & Wesfreid J.-E., The Eur. Phys J. E, 13, 213, 2004).

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